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# Water Availability for Agriculture in the United States

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Water availability is essential to the sustainability of modern society and has long been a central focus of conservation activities in the United States and associated conservation science. According to the US Geological Survey (USGS) Report to Congress, water availability is a function of water quantity, water quality, and the structures, laws, regulations, and economic factors that control its use (Norton and Groat 2002). The major sources of water that

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are used by society—precipitation, surface water supplies, and groundwater aquifers—are influenced over the long-term by climate and in the short-term by precipitation and temperature distribution.

Agriculture is the largest user of water in the United States, with crop production comprising 95.4% of total national consumptive water use (Marston et al. 2018). Precipitation provides 86.5% of water use for crop production, while surface water and groundwater aquifers provide 5.9% and 7.6%, respectively. Irrigation for growing corn, hay, rice, wheat, soybeans, cotton, and almonds represents 47% of national surface water consumption and 75% of national groundwater consumption. However, a national, spatially detailed assessment of water use by all major sectors of the economy in the United States reveals tremendous spatial variability in surface water and groundwater consumption and identifies local areas of significant competition for these resources (figure 1). The category of "other crops" in

**Figure 1**

**Sector with the largest consumption of surface water and groundwater resources in each US county. Agriculture is the largest water user in 2,164 of the 3,143 counties. In other counties, service industries (354), thermoelectric power generation (289), manufacturing (234), and mining (102) are the dominant water users (Marston et al. 2018).**

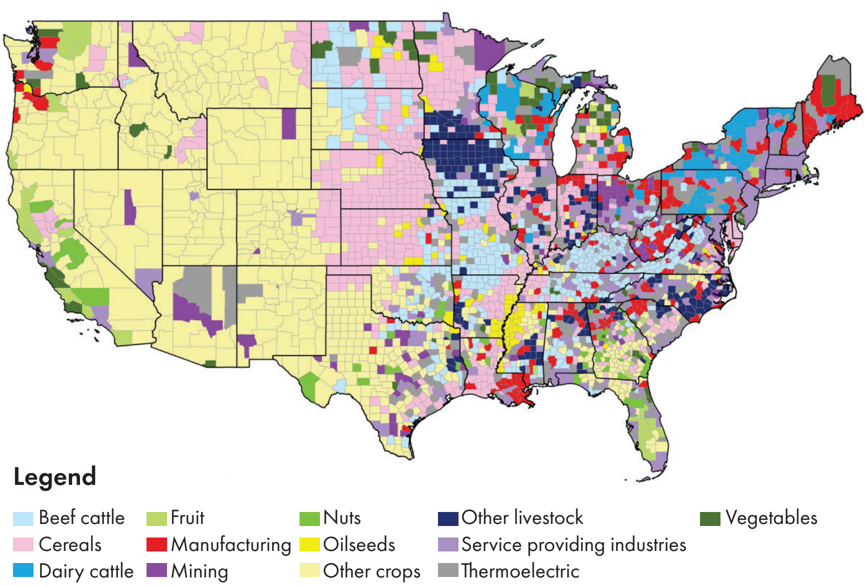

figure 1 (pale yellow) includes large areas of forest, rangeland, and desert in the western United States.

A patchwork of policies regulate water availability for agriculture in the United States. These range from the federal Clean Water Act (1972), which designates intended uses for different water sources and enforces action around protecting these uses, to state and local policies governing water resource rights and use (e.g., riparian versus prior appropriation). With over 30 federal agencies, boards, and commissions charged with overseeing the nation's water resources, there have been repeated calls to unify and simplify policies, all in the service of sustainable water use (Christian-Smith et al. 2011). These calls, along with incessant pressure to produce food, feed, fiber, and energy more efficiently, place a premium on understanding the diversity of water availability issues facing agriculture in the United States. This chapter reviews issues and challenges affecting water availability for agriculture in the Southeast and Southwest regions of the United States and in the Northeast, Midwestern, Great Plains, and Pacific Northwest regions of the United States and southern Canada. Research needed to address these issues and challenges is identified.

## Northeast

The Northeast, from the states of Pennsylvania, West Virginia, and Virginia to Maine and the southern parts of the Ontario, Quebec, and New Brunswick provinces, is blessed with abundant precipitation that supports a highly diverse (Aguilar et al. 2015), predominantly rain-fed agricultural industry that is vitally important to the economy and as a local food source for its inhabitants. Due to the Northeast's mountainous topography and expansive areas of marginal soils for agriculture, forest is the dominant land cover. Agriculture tends toward valley bottoms, on lake plains adjoining Lakes Erie, Ontario, and Champlain, and on the less steep topography near coastal areas. Dairy production in Pennsylvania, New York, Vermont, and southeastern Ontario, Quebec, and New Brunswick; beef production in the Virginias; and vegetable production in localized areas of New Brunswick, Maine, New York, New Jersey, and Virginia are major users of surface water and groundwater. Liquid manure management systems employed by dairy in the Northeast place especially high demands on surface water and groundwater resources. More importantly, water quality issues deriving from nutrient management associated with these agricultural enterprises affect the availability of water for other important uses, such as human consumption, fishing, and recreation. However, in most of the Northeast, overall consumption of surface water and groundwater resources by agriculture is minor compared to uses for service-providing industries, manufacturing, thermoelectric use, and mining (figure 1).

Given the limited footprint of agriculture in the Northeast compared with forests (by area) and urban sprawl (by intensity of resource consumption), factors affecting water availability for agriculture are often driven by nonagricultural priorities. For instance, providing an adequate public water supply for a large and growing urban population in the megalopolis that stretches from Washington, DC, to Boston is the foremost water availability concern in the Northeast. Water required for use as public water supply for this population exceeds that required to meet the needs of the population of the entire west coast by a third (Dieter et al. 2018). To illustrate the severity of concern for water availability for public consumption, consider water management in the Delaware River Basin, where three reservoirs, located in the headwaters, serve as public water supply for New York City and water drawn from near the mouth of the river serves as public water supply for Philadelphia. The Delaware River Basin Commission has the authority to declare a water supply emergency based on a drought or other condition that may cause a shortage of available water. The reservoirs may be forced to release water in order to maintain sufficient freshwater flow to keep saltwater from moving upstream and contaminating the Philadelphia water intake. The most severe drought emergency occurred in the 1960s, but drought emergencies were also declared in 1981, 1985, 1999, and 2001 (Delaware River Basin Commission 2019). Most major cities in the Northeast use surface waters as their municipal water source, but groundwater is locally important to many smaller towns and cities. Trenton, New Jersey, near to Philadelphia, relies on groundwater as its municipal water source, and the same saltwater encroachment that threatens Philadelphia's water source threatens the wells that tap Trenton's aquifer. Although much of Ontario receives drinking water from surface waters, many localized Canadian communities also rely on groundwater as their primary municipal water source.

Current and future changes in climate pose challenges for maintaining water availability in the Northeast (Tavernia et al. 2013). Changes in seasonal warming patterns, advances in high-spring streamflow, decreases in snow depth, extended growing seasons, and earlier bloom dates have already been observed (Hayhoe et al. 2007; Dupigny-Giroux et al. 2018). Moreover, shrinking snow cover, more frequent droughts, and extended low-flow periods in summer are predicted with climate warming. In coastal aquifers of the Northeast, saltwater intrusion poses a growing threat to drinking water supplies, as well as agricultural and industrial uses (Lall et al. 2018). These climate-driven challenges to maintaining adequate water supplies are further compounded by predictions of continued population growth in the Northeast (Jones and O'Neill 2013; US EPA 2019). Notably, the major metropolitan areas surrounding Boston, New York, Baltimore, and Philadelphia are projected to experience population increases of 20%, 11%, 12%, and 5%, respectively, by 2040 (Thomas 2016).

Although there has been a long history of irrigation in the region for high-value, specialty crops, this practice has been steadily growing over recent decades, including for agronomic crops and as a means of reusing wastewaters. Presently, about 7% of the Northeast's cropland is irrigated, with 67% of agricultural irrigation water sourced from groundwater (Dieter et al. 2018). In some cases, introducing irrigation may mitigate more frequent droughts that threaten yields of these high value crops, but only if water extraction does not compete with water needed for public water supplies. Heavily irrigated areas along the North Atlantic Coastal Plain, including the lower Delmarva Peninsula, have seen declining groundwater levels that are due in part to increases in irrigated areas (Russo and Lall 2017) as well as rising domestic consumption (Dong et al. 2019). Although a small number of farms in Ontario are irrigated, irrigation represents the greatest fraction (greater than 50%) of agricultural water use in the province (Ecologistics Limited 1993; de Loë et al. 2001), and in some cases, irrigation is used excessively (Bernier et al. 2010). In some areas of southwestern Ontario, groundwater is being withdrawn at a rate that exceeds natural recharge (Schellenberg and Piggott 1998). These trends bear careful watching, as irrigated areas are projected to expand with climate change throughout the Northeast (Sanderson 1993; Marshall et al. 2015).

Despite growing competition for surface water and groundwater between agricultural and nonagricultural sectors, competition that may be exacerbated with climate change, the most pressing research priorities related to water availability in the Northeast continue to undoubtedly involve water quality. The importance of water quality is evidenced by multistate and international programs to address problems in the Chesapeake Bay (Kleinman et al. 2019), Lake Champlain (Howland 2017), and Lake Ontario (Environment and Climate Change Canada and the US Environmental Protection Agency 2018). New and more effective strategies are needed for controlling sediment and nutrient losses from agricultural lands that threaten water quality and thereby limit water availability for commercial fishing and recreational use in the Chesapeake Bay, Lake Ontario, and Lake Champlain.

## Southeast

The climate of the Southeast (Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Tennessee following USGS definition) is a powerful driver of the region's agricultural economy. The region experiences generally mild temperatures and a relative abundance of sunshine and water resources, enabling a long and productive growing season. Most areas across the region receive an average of over 1,020 mm (40 in) of precipitation annually, which is typically sufficient to support a wide variety of crops (Kunkel et al. 2013).

Much of the Southeast tends to use less water from all sources as compared to other eastern states (Dieter et al. 2018). The use of irrigation in the Southeast has increased as farmers recognize its potential for improving yields and sustaining crops during periods of dry weather (Harrison 2001; Goklany 2002; Dukes et al. 2010). However, the proportion of water used in irrigation is generally low compared to other regions, with exceptions of Arkansas, Mississippi, and Florida. Competing interests between agriculture, conservation, recreation, and utilities makes appropriating limited water supplies difficult, especially in vulnerable basins where demand for water is high. Groundwater depletion is occurring in the Atlantic Coastal Plain in North Carolina, South Carolina, and Georgia; along the Gulf Coastal Lowlands of Alabama, Florida, and Louisiana; and in the Mississippi Embayment in Arkansas, Mississippi, and Louisiana (Konikow 2013; Kresse et al. 2014; Barlow and Clark 2011 ).

Changing climate is anticipated to have a major effect on water resources available for agriculture with significant implications for future crop production in the Southeast. The frequency and intensity of extreme heat and heavy precipitation events is rising (USGCRP 2017). These extremes could result in more frequent droughts of longer duration. Heavy precipitation events may lead to greater erosion and water loss in runoff, as opposed to infiltration and storage. Climate models predict increases of 40 to 50 days with temperature maximum over 32ºC (90ºF) in much of the Southeast (USGCRP 2017). Fall precipitation is decreasing in the Southeast, and the eastern half of the United States, including the Southeast, is experiencing the largest increases in extreme precipitation events (USGCRP 2017). Variable precipitation patterns strongly influence stream flow, which, in turn, impact riverine ecosystem integrity (physical aquatic habitat, water quality, connectivity, biota quantity, and diversity) (Anandhi et al. 2018). A survey of data from 1936 to 2016 determined that the greatest stream flows were in late spring, with the largest variability and the lowest flows in late summer to early fall (Anandhi et al. 2018). Other stressors to aquatic ecosystem sustainability over the past century include construction of impediments, such as weirs and dams, and changes in land use. Altering the natural flow of streams can negatively impact habitat and diversity in these systems. Some trends in water and land use in the Southeast that impact stream flow include the conversion of land from forest to agriculture during the early part of the $20^{th}$ century, regeneration of forests during mid-$20^{th}$ century, increased irrigation, and increased urbanization in the latter portion of the $20^{th}$ century and early $21^{st}$ century (Anandhi et al. 2018; Massey et al. 2017; Yasarer et al. 2020).

Continued aquifer declines due to increased use of groundwater for irrigation, decreasing stream flow, increased periods of drought due to variability in precipitation patterns, decreased land available for crops, and extreme rainfall events are water resource challenges facing agriculture in the Southeast. Better water management through precision irrigation, implementation of conservation practices that increase soil water storage and decrease runoff, improvements in storage of stormflow, and development of more water efficient crops offer opportunities to mitigate the negative impacts of these patterns. Conservation practices that improve soil carbon present a win-win situation for agriculture, mitigating climate change while improving soil water storage. In addition, a better accounting of agricultural water use is critical to facing increasing urban, industrial, and environmental water demands.

## Midwest

The Midwest (Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, Wisconsin, and southern Ontario, Canada) sits adjacent to four of the Great Lakes and is blessed with an abundant supply of water resources. The unique combination of glacially derived soils and cool, humid climate in the Midwest make it one of the most intense and productive agricultural areas in the world, generating approximately 65% of the US corn and soybean production (Pryor et al. 2014; NOAA 2013) and about half of Canadian soy and corn production. In addition to its agricultural significance, the Midwest tourism industry depends heavily on the Great Lakes and its many miles of shoreline. Water supply for the 61 million people (20% of the US population) who call the Midwest home originates primarily from surface sources.

Annual precipitation across the Midwest varies from greater than 1,150 mm (45 in) along the Ohio River and Missouri to less than 625 mm (25 in) in northern Minnesota while snowfall depths range from approximately 25 mm (1 in) in the southern latitudes to greater than 5,000 mm (197 in) in the Upper Peninsula of Michigan (NOAA 2013). The precipitation distribution also varies across the region with greater precipitation generally in the spring and summer. Midwest agricultural production is dependent on this precipitation distribution. However, excess precipitation in the spring often leads to localized flooding and prevents field access for farming practices. Excess water in the spring is often removed through artificial surface or subsurface drainage

(Blann et al. 2009) to facilitate agricultural crop production and reduce localized flooding concerns. Between 18 and 28 million ha (45 and 70 million ac) of cropland in the Midwest benefits from subsurface tile drainage (Zucker and Brown 1998), with drainage intensity continuing to increase (Sugg 2007; Blann et al. 2009).

The Midwest has historically been plagued by extreme rainfall events leading to extensive flooding and loss of life. For example, the 1913 flood in Ohio resulted in greater than 450 deaths and approximately 40,000 homes lost or destroyed, and has been referred to as Ohio's greatest weather disaster. Following the Ohio 1913 flood, conservancy districts were established to develop plans for preventing and/or addressing future flooding. The 1993 Mississippi River flood forced the prolonged closure of roads, bridges, railroads, and river traffic, and the losses to agricultural production and personal property were catastrophic (NOAA 2013). Most Midwest floods result from extreme precipitation; however, spring snowmelt can also lead to localized flooding (Kunkel 2003).

The greatest current water availability related issue in the Midwest is not supply but quality, and this water quality impairment is in large part due to artificial subsurface tile drainage (David et al. 2010; Maccoux et al. 2016). Indeed, in 2014, the city of Toledo issued a "Do Not Use" drinking water warning due to toxins related to a harmful algal bloom in Lake Erie, and many other streams and watersheds within the Midwest have been listed as impaired. In Iowa, several lawsuits have been filed over water quality concerns and the role agriculture plays in water quality. In Flint, Michigan, a major water quality crisis that received national attention developed when thousands of residents were exposed to lead in their finished drinking water. Furthermore, the tourism industry has been negatively impacted from poor water quality as many beaches along the Great Lakes and inland water bodies are forced to issue periodic warnings regarding water quality and human contact. As shifts in local weather and climate occur, water quality concerns will be exacerbated (Pryor et al. 2014; Verma et al. 2015).

Climate shifts and climatic variability predictions for the Midwest suggests warmer and wetter winter and spring months, a greater frequency of intense storms throughout the year, and more severe and longer droughts in the summer (Takle and Hofstrand 2008; USGCRP 2009), taxing an already weak infrastructure and exacerbating future water quantity and quality concerns. Decreased precipitation in the summer suggests agricultural watersheds will be subjected to increased water withdrawals for irrigation purposes (Wuebbles and Hayhoe 2004) creating a major shift in water usage and putting pressure on surface water resources. If supplemental water is not available, increased growing season drought conditions will lead to a reduction in crop yields. Furthermore, nutrient loss and availability are expected to be impacted under these future climate scenarios (Robertson et al. 2013; Jarvie et al. 2013) and directly impact water quality. Projected increases in temperatures and humidity are expected to exacerbate air and water quality degradation, increasing public health risks (Pryor et al. 2014). As pressure to produce more food, feed, fiber, and fuel from our agricultural lands increases and climate shifts occur, it will be increasingly important to balance social, economic, and environmental concerns.

## Great Plains

The Great Plains, which covers parts of Canada and the United States, is usually a windy and periodically dry region. Here we discuss the Great Plains water resources in the United States that cover all or parts of Colorado, Kansas, Montana, Nebraska, North Dakota, Oklahoma, South Dakota, Texas, Wyoming, and southern parts of Manitoba and Saskatchewan, Canada. Water availability in this region is driven by climate and mainly irrigation water use (Council of Canadian Academies 2013; Wishart 2019). As with other regions of the country, climate is the largest driver of water availability, with precipitation accounting for all surface water and a significant portion of groundwater recharge. In general, rainfall and snowfall increase from west to east varying from 350 to more than 1,000 mm (14 to more than 40 in) annually and vary from one year to the next (Whishart 2019). The climate in the Great Plains is characterized by extended periods of dry and wet years (Garbrecht 2008). In the Northern Great Plains, soil moisture reserves are sustained by snowmelt and can therefore vary considerably from year to year (Pomeroy et al. 2005). In very dry years, widespread crop failure results, and in very wet years, flooding occurs, particularly around snowmelt, damaging agricultural infrastructure (Pomeroy et al. 2005). Temperature affects evapotranspiration rates during the growing periods and the length of the growing season, with number of frost-free days ranging from more than 200 days in the Southern Plains to less than 100 days in the Northern Plains (Wishart 2019). According to Zou et al. (2018), areas in the far northern Great Plains had increasing open-surface water body area for the 1984 to 2016 period while the southern Great Plains had a decreasing trend for the same period. Shook and Pomeroy (2012) have shown that the occurrence of multiday storms in summer is increasing across the Northern Plains, which has implications for increased flow in summer. These climate-driven divergent open-surface water body area trends have serious consequences for water resources, especially in the water-poor parts of the Great Plains.

Water resources comprise of both groundwater and surface water. Surface water sources include natural streams, lakes, manmade dams, and flood retarding reservoirs. In the Great Plains region, there are 80 large multiuse reservoirs with a total capacity of $2.8 \times 10^{10}$ $m^3$ (22.9 million ac-ft) of water (Wishart 2019). Also, there are thousands of smaller, headwaters flood control reservoirs implemented, especially in the southern Great Plains, as a result of the Watershed Protection and Flood Prevention Act of 1954 (Hanson et al. 2007; Hunt et al. 2011). Over time, these dams and reservoirs that were built several decades ago lose water storage capacity due to sediment that is eroded from overland, transported downstream, and deposited in the reservoir (Morris and Fan 1998; Moriasi et al. 2018; Randle et al. 2019). One of the consequences of continuous dam and reservoir sedimentation is the reduction in the reliability of surface water supply.

Irrigation withdrawal for crop production is the biggest user of water resources, especially in the southern Great Plains. Irrigation that was introduced to the region by the Spanish settlers before 1700 initially utilized surface water (Whishart 2019). However, surface water body area shrinkage due to climate change as well dam and reservoir sedimentation over time has led to huge groundwater extractions for irrigated agriculture, which furthers surface water body area shrinkage, especially in the southern Great Plains (Zou et al. 2018). The classic example of the effects of groundwater overexploitation on water resources is the Ogallala Aquifer, the largest aquifer in North America (McGuire 2014; Gowda et al. 2019). The Ogallala Aquifer underlies an area of 450,000 $km^2$ (175,000 $mi^2$) spanning parts of Texas, Oklahoma, Kansas, New Mexico, Colorado, Nebraska, Wyoming, and South Dakota, i.e., the High Plains Region. The irrigated area of the High Plains Region has significantly increased since 1949 when pumping began, which has led to declines in groundwater storage (McGuire 2014; Gowda et al. 2019).

As a result of the declines in both surface and groundwater resources, especially in the southern Great Plains, compounded by impacts anticipated with climate change, new management strategies will be needed to ensure that surface water (Randle et al. 2019) and groundwater (Gowda et al. 2019) resources can sustain food production and other water uses. Strategies that improve water use efficiency, such as by incorporating drip irrigation; adopting cropping systems that require less water; and utilizing management systems that improve efficient infiltration, storage, and use of precipitation so that supplemental irrigation requirements are reduced, must be developed. Many surface water bodies in the Great Plains, particularly Lake Winnipeg (Schindler et al. 2012), have been severely impacted by water quality issues resulting from agriculture, and the nutrient loads are especially difficult to control due to the climate of the region (Council of Canadian Academies 2013). Thus, improving water resource use efficiency also requires optimizing the selection and strategic placement of conservation practices on the landscape to reduce soil erosion and improve water quality, as well as utilizing improved nutrient management strategies that apply only what crops need for optimal crop production while reducing excess nutrients transported into surface water bodies or leached into groundwater. Research is required to improve understanding of key soil, hydrologic, and agroecosystem processes that control water quality and quantity, and support the development of tools and techniques to improve watershed integrity and related ecosystems services.

## Pacific Northwest

Water availability in the Pacific Northwest region of the United States (Washington, Oregon, Idaho, and northern California) and southern British Columbia, Canada, is highly dependent on winter mountain snowpacks. Snowfall in this region can represent between 50% to 70% of annual precipitation totals (Serreze et al. 1999), with maritime to intercontinental snowpacks in the different ecoregions across the Pacific Northwest (Trujillo and Molotch 2014). These vital natural water towers provide timely delivery of water, with further man-made reservoirs regulating water yields for ecological functions, energy generation, and water supply for human consumption and agriculture while simultaneously protecting from effects of droughts and floods.

The Pacific Northwest is generally warm and dry in the summer months and cool and wet in the winter months. However, due to complex interactions between the onshore jet stream and mountain topography, the Pacific Northwest can be further subdivided into a variety of smaller ecoregions. In coastal Washington, Oregon, and northern California, precipitation totals are the highest in the conterminous United States, with a significant portion of winter precipitation falling as snow. Further inland, the mountains of Idaho and eastern Oregon and Washington, along with southern British Columbia, Canada, are colder and exhibit a higher snow proportion of annual precipitation. These snowpacks then supply runoff to the Columbia River, the fourth largest US river basin by volume. To the south, the Columbia's largest tributary, the Snake River, flows across Idaho's large high desert southern plain and is crucial for much of the region's agriculture.

Regional annual mean temperatures over the last century have risen by approximately 1ºC (2ºF), with the majority of the increases occurring during winter snow accumulation months (Abatzoglou et al. 2014; Mote et al. 2014). Future climate scenarios depend on current and future greenhouse gas emissions, but overall paint a dark picture. Under current emissions scenarios, temperatures across the Pacific Northwest are projected to rise 4ºC to 10ºC (7ºF to 18ºF) by the end of the century (May et al. 2018; RMJOC-II 2018). At the same time, future precipitation trends are less certain due to uncertainties in the Global Climate Models that underpin the projections (Abatzoglou et al. 2014; Kormos et al. 2016), but many projections agree that precipitation will generally increase throughout the winter and decrease in summer months (Jiang et al. 2018; Shrestha et al. 2014). However, even the combination of warmer winter months and an unchanging precipitation scheme will result in decreases in the snow proportion of annual precipitation, reduced mountain snowpacks, and decreased summer streamflow (Mote et al. 2014). Mountain basins that rely on large snowpacks for streamflow production will be the most sensitive to warming temperatures because winter flows will increase, and the annual spring melt timing will come earlier. These changes to the regional water cycle will have dire consequences on agricultural production, hydroelectric energy production, reservoir operations for both flood and drought mitigation, aquatic ecology, and forest fire severity.

Across the Pacific Northwest, continued reduction and increased variations in western mountain snowpack storage of water will continue to drive competing demands for available surface water from agriculture, urban use, energy production, and environmental flow requirements. The use of groundwater to offset available streamflow will continue to increase the challenges of decreasing groundwater levels and the need to increase recharge potential. Enhanced snowpack water measurement and stream flow prediction technologies provide opportunities to improve reservoir management needed to offset periods of inadequate surface water availability and to allocate excess surface water for groundwater recharge during periods of high runoff. Improved crop water use efficiency, recovery of agricultural soil quality, and control of agricultural impacts on water quality all provide additional opportunities to offset regional water management issues by reducing agricultural impacts on water supplies.

### Southwest

The Southwest (Arizona, California, Colorado, Nevada, and New Mexico), naturally hot and dry, faces water supply shortages that will only worsen with time. John Wesley Powell, who led a boat expedition down the Colorado in 1869 and served as the second director of the USGS, famously said, “I tell you gentlemen you are piling up a heritage of conflict and litigation over water rights, for there is not enough water to supply the land” (Pitzer 2019). Powell argued in vain for sparse settlement designed around watersheds. Instead, with the help of significant federal investment in water management infrastructure, the Southwest developed irrigated agriculture, and later, large urban areas like San Diego, Los Angeles, Las Vegas, Phoenix, Tucson, Denver, and Albuquerque that expanded the region's population to 60 million. Most of the water used (three-quarters of the total in 2010 for all southwestern states except Colorado) goes to irrigated agriculture and intensive livestock production (Gonzales et al. 2018). Although only a small fraction of the Southwest's water is transferred though water markets, and such markets face a patchwork of legal and practical constraints, the role of water markets in the Southwest is expected to increase with water scarcity (Schwabe et al. 2020).

In addition to increasing demand from a growing population, the Southwest faces additional challenges to its water supply. Rising temperatures, in addition to decreased precipitation, result in "aridification," or a more permanent water shortage than is conveyed by the term drought: Colorado River flows from 2000 to 2014 were 19% below the 1906 to 1999 average because of reduced snowpack and increased evapotranspiration (Udall and Overpeck 2017). There is also a "structural deficit" in that the basis of the 1922 Colorado Compact and later agreements provided for the use of $9.3 \times 10^9$ $m^3$ (7.5 million ac-ft) on average over a 10-year period for both the upper (Wyoming, Colorado, New Mexico, and Utah) and lower (Arizona, California, and Nevada) basins, plus $1.9 \times 10^9$ $m^3$ (1.5 million ac-ft) to Mexico, exclusive of prior rights and evaporative demand from reservoirs. Unfortunately, tree-ring studies indicate that long-term flows at Lee Ferry may range between $1.6 \times 10^{10}$ to $1.8 \times 10^{10}$ $m^3$ (13 to 14.7 million ac-ft), rather than the $2.0 \times 10^{10}$ $m^3$ (16.4 million ac-ft) anticipated in the Colorado Compact (National Research Council 2007). The result is that Lake Mead is close to the 325 m (1,070 ft) elevation level that will trigger a shortage declaration on the lower Colorado River. At the first level of the shortage declaration, the drought contingency plan would result in a 25% to 40% reduction in surface water deliveries to Arizona. The reductions would almost entirely be borne by agriculture, with up to 40% of agricultural fields fallowed in Maricopa and Pinal counties. "The impact of fallowing land in Pinal County could result in more than $200 million in lost agricultural revenues, and job losses up to 6% of the workforce" (Bickel et al. 2018). In the near term this shortage could be offset by groundwater pumping. However, this is a short-term solution, as Thomas and Famiglietti (2019) report that groundwater, the buffer of last resort, is being depleted during periods of precipitation deficits. In summary, water supply, always a limiting factor in the Southwest, will become an even more binding constraint. Research is needed to improve water efficiency in irrigated agriculture, increase flexibility of livestock operations in the face of drought, assess the impact of declining flows on salinity in the Colorado River basin, expand the use of degraded and brackish waters, and better quantify water budgets and increase recharge in rural areas.

## Summary

The sustainability of agriculture in the United States is inexorably linked to the availability of water resources, although factors affecting water availability vary widely. Water availability for agriculture has historically been controlled by the water cycle, but, increasingly, quality of water resources as affected by agricultural practices restricts their availability for other important uses. Ensuring long-term water availability requires adaptation to changing climate, implementation of comprehensive conservation strategies, and an evolution of agricultural production systems. Fortunately, the United States is well positioned to meet critical research needs in support of ensuring water availability in the face of climate change. National research networks, such as the National Ecological Observatory Network, the Long-Term Ecological Research Network, and the Long-Term Agroecosystem Network, are organized to address local and regional research needs and extrapolate results to national scale. For more information related to the subject of water availability, readers are encouraged to read chapters in this book on the topics of water quality, irrigation, drainage, climate change, and modeling.

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